# Magnetization of undoped 2-leg $S = \frac{1}{2}$ spin ladders in $La_4Sr_{10}Cu_{24}O_{41}$

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Magnetization data of single crystalline $La_4Sr_{10}Cu_{24}O_{41}$ are presented. In this compound, doped spin chains and undoped spin ladders are realized. The magnetization, at low temperatures, is governed by the chain subsystem with a finite interchain coupling which leads to short range antiferromagnetic spin correlations. At higher temperatures, the response of the chains can be estimated in terms of a Curie-Weiss law. For the ladders, we apply the low-temperature approximation for a $S = 1/2$ 2-leg spin ladder by Troyer et al.

The compounds $(Sr, Ca, La)_{14}Cu_{24}O_{41}$ possess an incommensurate layered structure of two alternating subsystems[1]. In these subsystems, two quasi one-dimensional (1D) magnetic structures are realized which are oriented along the $c$-axis, i.e. $S = \frac{1}{2}$ $Cu_2O_3$ spin ladders and $CuO_2$ spin chains. Since the spin ladders exhibit a considerable spin gap $\Delta$ of several hundred Kelvin, the low temperature magnetic response of these compounds is described in terms of the weakly coupled $CuO_2$ spin chains[5]. In addition, the compounds $Sr_{14-x}Ca_xCu_{24}O_{41}$ are intrinsically hole doped with six holes per formula unit. $La^{3+}$ doping leads to an decrease of the hole content in both the ladder and the chain subsystem. For $La_x(Ca, Sr)_{14-x}Cu_{24}O_{41}$, with $x \geq 3$, the holes completely reside at chain sites[2]. The magnetic coupling of Cu-spins via a hole is antiferromagnetic (AF) while a ferromagnetic (FM) superexchange is realized for adjacent Cu spins. Interchain coupling leads to a 3D AF spin ordering for $x \geq 5$, below $\sim$10 K.

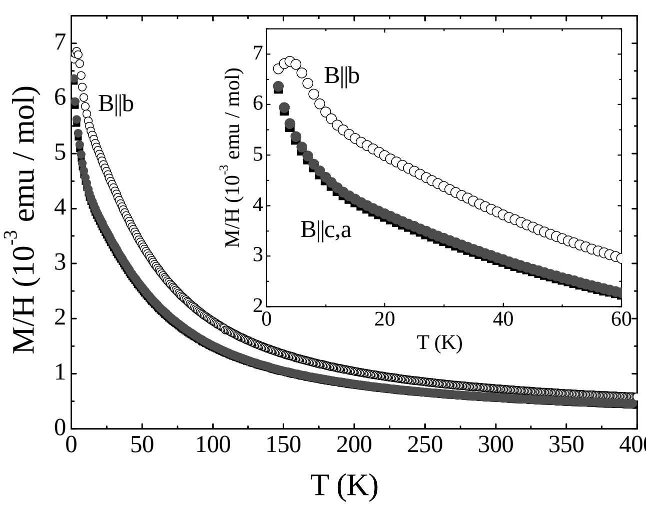


FIG. 1: Static Susceptibility $M/H$, with $\mu_0 H = 1\,\mathrm{T}$ applied along the $a$, $b$, and $c$-axis, respectively. The inset highlight the low temperature regime.

The magnetization data in Fig. 1 mainly reflect the chain magnetism. At high temperatures, i.e. at 400 K, the anisotropy is well explained by the anisotropic $g$-factor ($g_\perp \approx 2.35$ and $g_\parallel \approx 2.05$) and the anisotropy of the Van-Vleck magnetism. These extracted values for $g$ agree well with recent ESR data[3]. Upon cooling, an approximate Curie-Weiss behavior is observed, with an additional upturn of $M$ below $\sim$10 K and a maximum for $B \| b$ at 4 K. The exact origin of the low temperature features of the magnetization is unknown but we recall that, in $La_4Sr_{10}Cu_{24}O_{41}$, along the chains there are several competing magnetic interactions, i.e. a FM nearest neighbor coupling, an AF next-nearest neighbor coupling and an AF coupling via the $\sim$20% of holes. In addition, there is an AF interchain coupling, which yields strong AF spin correlations with an easy axis parallel to the $b$-axis as it is reflected by the data. Long range AF spin order, however, does not evolve above 2 K.

At high temperatures, i.e. $T \gtrsim 140$ K, the magnetization of the chains can be described in terms of the Curie-Weiss law

$$\chi(T) = \chi_0 + \frac{C}{T + \Theta}. \qquad (1)$$

In addition to the chain magnetism, the magnetic response of the ladders has to be considered at higher temperatures. The spin gap of the ladders leads to an exponential increase of the $\chi_{\mathrm{ladders}}$. Within the low-temperature approximation for a $S = 1/2$ 2-leg spin ladder, the ladder contribution to the susceptibility $\chi_l$ may be described by

$$\chi_l(T) = \frac{A}{\sqrt{T}} e^{-\Delta/(k_B T)}, \qquad (2)$$

with $\Delta$ being the spin gap[?] . For the analysis of the magnetization data, we hence fitted our data by the sum of Eqs. 1 and 2. We fixed the spin gap to the value of $\Delta \simeq 313$ K known from neutron scattering on the same compound[7]. We restricted the analysis to temperatures above 140 K. The results of this procedure, for $B \| a$, are displayed in Fig. 2. Apparently, the data are reasonably well described by Eqs. 1 and 2 at $T \gtrsim 140$ K. At low temperatures below 140 K, however, there are strong deviations which we attribute to the fact that, in this temperature regime, due to the intrachain couplings the chain response can not be described by a Curie-Weiss law. Quantitatively, the analysis yields reasonable results for the chain magnetism, i.e., $C_a = (0.152 \pm 0.1)$ erg K/(G$^2$mol Cu), $C_b = (0.196 \pm 0.1)$ erg K/(G$^2$mol Cu), and $\Theta \approx 1$ K.

For the ladders, we obtain:

$$A_{a,c} = (1.7 \pm 0.1) \cdot 10^{-3}\,\mathrm{erg}\,\sqrt{\mathrm{K}}/(\mathrm{G}^2\mathrm{molCu}),$$

$$A_b = (1.46 \pm 0.1) \cdot 10^{-3}\,\mathrm{erg}\,\sqrt{\mathrm{K}}/(\mathrm{G}^2\mathrm{molCu}).$$

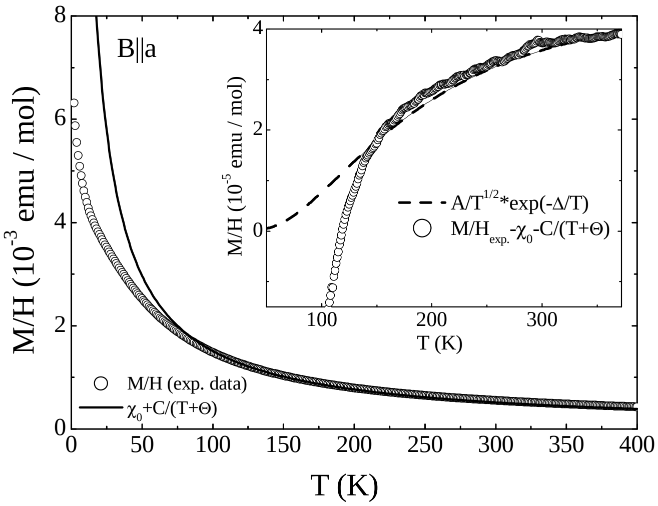


FIG. 2: Static susceptibility $M/H$ (data points) and magnetic response of the chains (dashed line) as described by Eq. 1 for high temperatures. Inset: Curie-Weiss-like susceptibility subtracted from the experimental data (data points) and magnetic susceptibility of isolated 2-leg ladders (dashed line).

The value of the parameter $A$ changes significantly if the chemically undoped compound $Sr_{14}Cu_{24}O_{41}$ is considered. Here, the spin gap of the ladders amounts to $\Delta = 377\,\mathrm{K}$.[8] Analyzing the data presented in Ref.[5] in the same way as described above yields

$$A_c = (4.1 \pm 0.1) \cdot 10^{-3}\,\mathrm{erg}\,\sqrt{\mathrm{K}}/(\mathrm{G}^2\mathrm{molCu}).$$

We mention that, in $Sr_{14}Cu_{24}O_{41}$, the fitting has to be restricted to $T > 200\,\mathrm{K}$ since there is a charge ordering transition below that temperature[9]. Moreover, in $Sr_{14}Cu_{24}O_{41}$ the ladders contain a considerable amount of holes while there are no holes in the ladders of $La_4Sr_{10}Cu_{24}O_{41}$.

In summary, we have presented the magnetization of the spin chain and spin ladder compound $La_4Sr_{10}Cu_{24}O_{41}$. The low temperature response is governed by the chain subsystem in which interchain couplings lead significant AF correlations. At high temperatures the chain magnetism follows the Curie-Weiss law. Additional contributions to the magnetization are due to the undoped spin ladders.


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